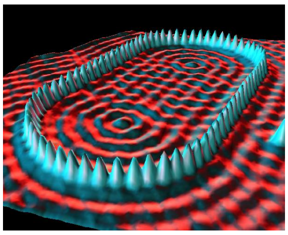
Kvantfysik

Har jag använt någon bild som jag inte får använda? Låt mig veta så tar jag bort den.
christian.karlsson@ckfysik.se

Uppdaterad: 171211

[1] Läget runt 1920
[2] Materiens vågegenskaper (de Broglie)
[3] Men kan det vara så här? (Elektroner och gitter)
[4] Men kan det vara så här? (Elektroner och dubbelspalt)
[5] Materiens vågegenskaper (Schrödinger – Born)
[6] Kvantmekanik (tidig)
[7] Kvantmekanik (tidig)
[8] Heisenbergs obestämdhetsrelation
[9] Läget runt 1927
[10] Efter 1927
[11] Läget idag
[12] Läget idag

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + U\psi$$



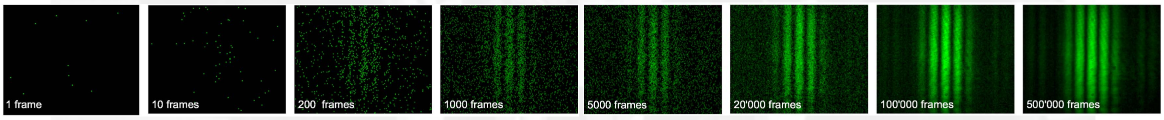
[1]

Since this experiment lasted for more than 30 minutes, I have sped the move up. Interference fringes are now clearly visible.

[2]

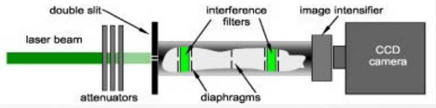
Läget runt 1920

	Partikelegenskaper	Vågegenskaper
Materia	$p = mv \quad W_k = \frac{mv^2}{2} \quad \boxed{\boldsymbol{R} = \dot{\boldsymbol{p}}}$ Ja! (mekanik) $p = \gamma mv \quad E_k = (\gamma - 1)mc^2$	?
Strålning	$p = \frac{h}{\lambda} \quad W = hf$ Ja! (fotonmodellen)	$\boldsymbol{E}, \boldsymbol{B}$ Ja! (elektromagnetism, optik)



[9]

Dubbelspaltexperiment med fotoner (2005)



Materiens vågegenskaper

Einstein (1916):

Fotoner: $p = \frac{h}{\lambda} \Rightarrow \lambda = \frac{h}{p}$


[10]

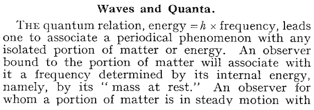
de Broglie (1924):

Varje partikel kan tillskrivas en våglängd $\boxed{\lambda = \frac{h}{p}}$

"materievåglängd"

Plancks konstant

partikelns rörelsemängd

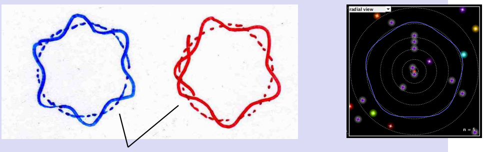


Waves and Quanta.

The quantum relation, energy $= h \times$ frequency, leads one to associate a periodical phenomenon with any isolated portion of matter or energy. An observer bound to the portion of matter will associate with it a frequency determined by its internal energy, namely, by its "mass at rest." An observer for whom a portion of matter is in steady motion with

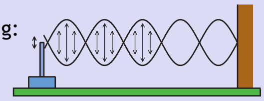
[11]

Ger en slags förklaring till väteatomens kvantiserade energinivåer:

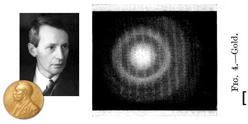


villkoret $2\pi r = n\lambda$ måste vara uppfyllt

Jfr stående våg på sträng:

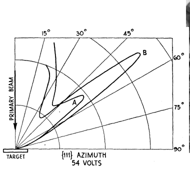


Bekräftades 1927



[12]

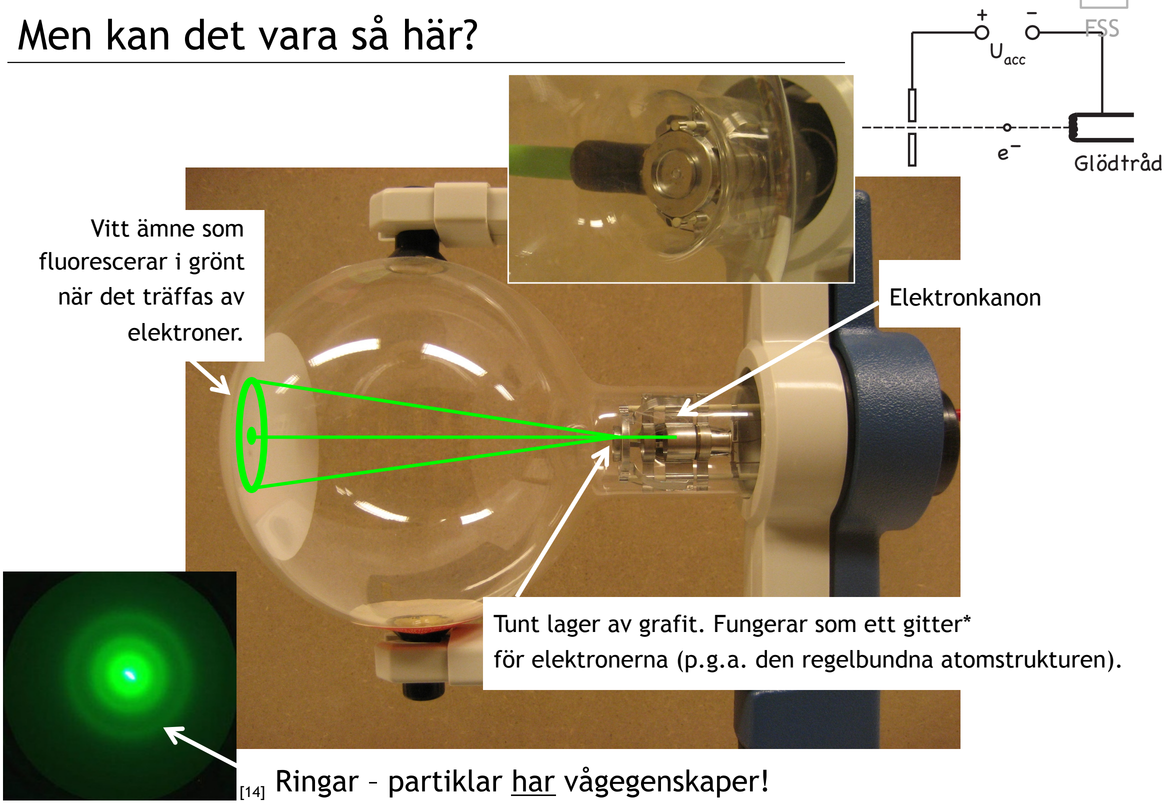
G. P. Thomson (UK)



[13]

Davisson & Germer (USA)

Men kan det vara så här?



Vitt ämne som fluorescerar i grönt när det träffas av elektroner.

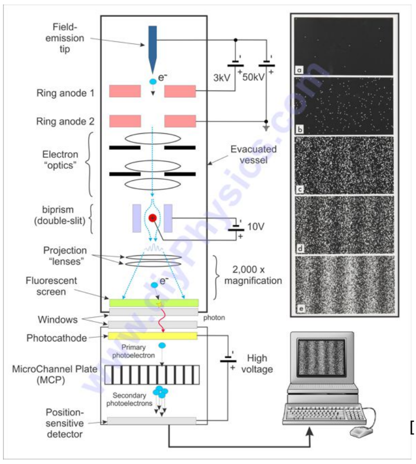
Elektronkanon

Tunt lager av grafit. Fungerar som ett gitter* för elektronerna (p.g.a. den regelbundna atomstrukturen).

[14] Ringar – partiklar <u>har</u> vågegenskaper!

Men kan det vara så här?

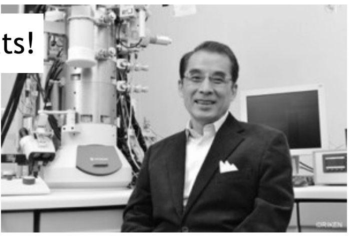
Dubbelspaltmönster med elektroner har observerats!



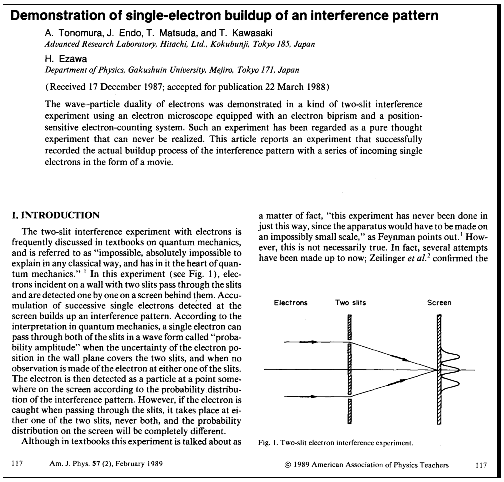
[15]

Since this experiment lasted for more than 30 minutes, I have sped the move up. Interference fringes are now clearly visible.

https://www.youtube.com/watch?v=5oQWtcfZN4M



[16]



Demonstration of single-electron buildup of an interference pattern

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(Received 17 December 1987; accepted for publication 22 March 1988)

The wave–particle duality of electrons was demonstrated in a kind of two-slit interference experiment using an electron microscope equipped with an electron biprism and a position-sensitive electron-counting system. Such an experiment has been regarded as a pure thought experiment that can never be realized. This article reports an experiment that successfully recorded the actual buildup process of the interference pattern with a series of incoming single electrons in the form of a movie.

I. INTRODUCTION

The two-slit interference experiment with electrons is frequently discussed in textbooks on quantum mechanics, and is referred to as "impossible, absolutely impossible to explain in any classical way, and has in it the heart of quantum mechanics."[1] In this experiment (see Fig. 1), electrons incident on a wall with two slits pass through the slits and are detected one by one on a screen behind them. Accumulation of successive single electrons detected at the screen builds up an interference pattern. According to the interpretation in quantum mechanics, a single electron can pass through both of the slits in a wave form called "probability amplitude" when the uncertainty of the electron position in the wall plane covers the two slits, and when no observation is made of the electron at either one of the slits. The electron is then detected as a particle at a point somewhere on the screen according to the probability distribution of the interference pattern. However, if the electron is caught when passing through the slits, it takes place at either one of the two slits, never both, and the probability distribution on the screen will be completely different.

Although in textbooks this experiment is talked about as a matter of fact, "this experiment has never been done in just this way, since the apparatus would have to be made on an impossibly small scale," as Feynman points out.[1] However, this is not necessarily true. In fact, several attempts have been made up to now; Zeilinger *et al.*[2] confirmed the

Fig. 1. Two-slit electron interference experiment.

117 Am. J. Phys. 57 (2), February 1989 © 1989 American Association of Physics Teachers 117

[17]

Kvantmekanik (tidig)

(en formulering av)

I kvantmekaniken (1925-26) beskrivs partiklar med vågfunktioner $\psi(\boldsymbol{x},t)$

har att göra med sannolikheten att hitta en partikel i (x, t)

Vågfunktionen för en elektron i första skalet i en väteatom (fås om man löser Schrödingerekvationen för väteatomen):

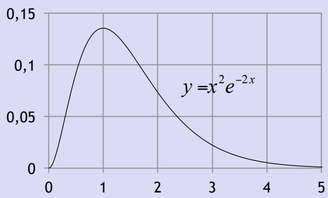
$$\psi_{100}(\boldsymbol{r}) = \frac{1}{\sqrt{\pi}}\left(\frac{1}{a_0}\right)^{\frac{3}{2}} \mathrm{e}^{-\frac{r}{a_0}},$$

där

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{\mu e^2}.$$

Sannolikheten att hitta elektronen mellan avstånden R_2 och R_1 (från kärnan):

$$P(R_2, R_1) = 4\pi\int_{R_1}^{R_2} r^2\psi_{100}^2 \mathrm{d}r$$



[18]

Heisenberg

[19]

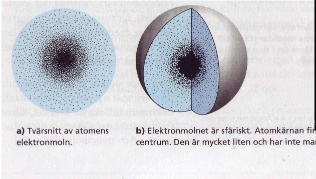
Schrödinger

[20]

Dirac

[21]

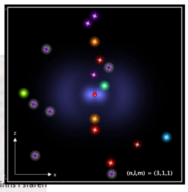
Born



a) Tvärsnitt av atomens elektronmoln.

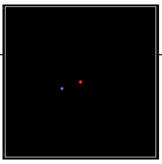
b) Elektronmolnet är sfäriskt. Atomkärnan finns i sfären centrum. Den är mycket liten och har inte markerats.

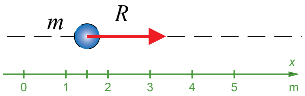
19



[22]

Kvantmekanik (tidig) vs. klassisk mekanik





Lägesfunktion

Newton II

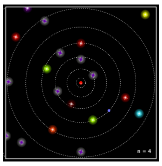
Klassisk mekanik $x(t)$ $$R = m\frac{\mathrm{d}^2x}{\mathrm{d}t^2}$$

Representerar omgivningens inverkan

Kvantmekanik $\psi(x,t)$ $$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + U\psi$$

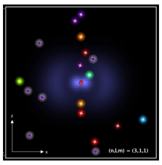
Vågfunktion

Schrödingerekvationen



Sannolikheten att hitta partikeln mellan x_1 och x_2:

$$P(x_1,x_2) = \int_{x_1}^{x_2} |\psi|^2 \,\mathrm{d}x$$



Heisenbergs obestämdhetsrelation

[29]

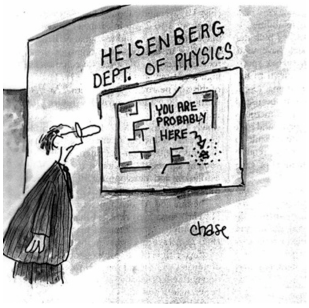
Heisenberg (1927):

Omöjligt att bestämma en partikels läge och rörelsemängd samtidigt!

$$\boxed{\Delta p_x \cdot \Delta x \geq \frac{h}{4\pi}}$$

oskärpa i rörelsemängd

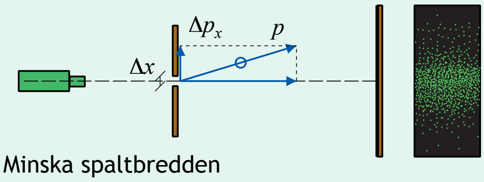
oskärpa i läge



[30]

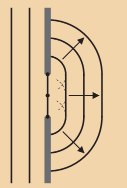
Ex: Ljus genom enkelspalt

Använd fotonmodellen och betrakta en foton i spaltöppningen. Fotonens rörelsemängd är $\vec{p}$



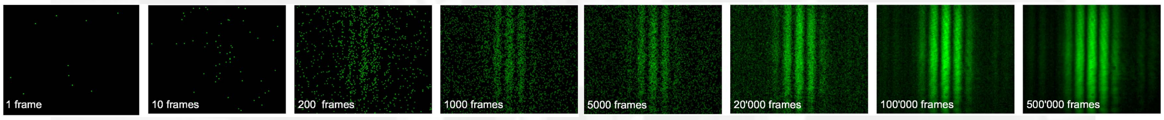
Minska spaltbredden
→ mindre Δx → större Δp_x
→ mer utsmetad intensitetsfördelning

Jfr vågmodellen:

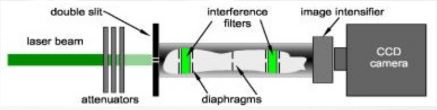


Läget runt 1927

	Partikelegenskaper	Vågegenskaper
Materia	$p = mv \quad W_\mathrm{k} = \frac{mv^2}{2} \quad \boxed{\boldsymbol{R} = \dot{\boldsymbol{p}}}$ Ja! (mekanik) $p = \gamma mv \quad E_\mathrm{k} = (\gamma - 1)mc^2$	$\lambda = \frac{h}{p} \quad \boxed{i\hbar \frac{\partial \psi}{\partial t} = -\frac{\hbar^2}{2m} \frac{\partial^2 \psi}{\partial x^2} + U\psi}$ Ja! (kvantmekanik)
Strålning	$p = \frac{h}{\lambda} \quad W = hf$ Ja! (fotonmodellen)	$\boldsymbol{E}, \boldsymbol{B}$ Ja! (elektromagnetism, optik)

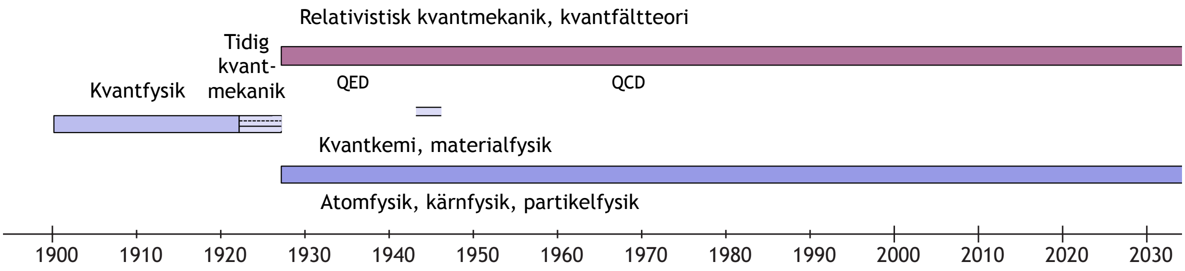


Dubbelspaltexperiment med fotoner (2005)

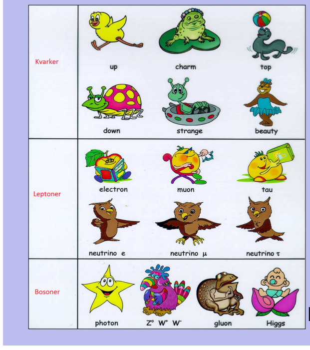


[9]

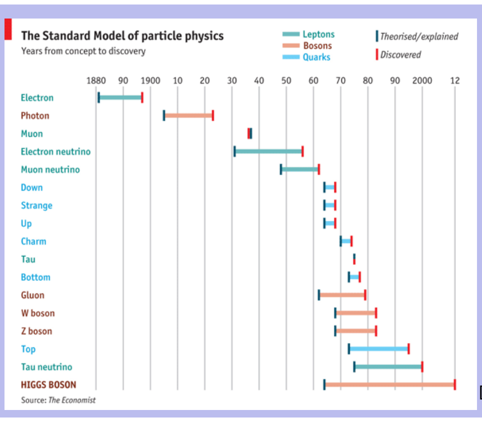
Efter 1927?



Partikelfysikens standardmodell



[31]

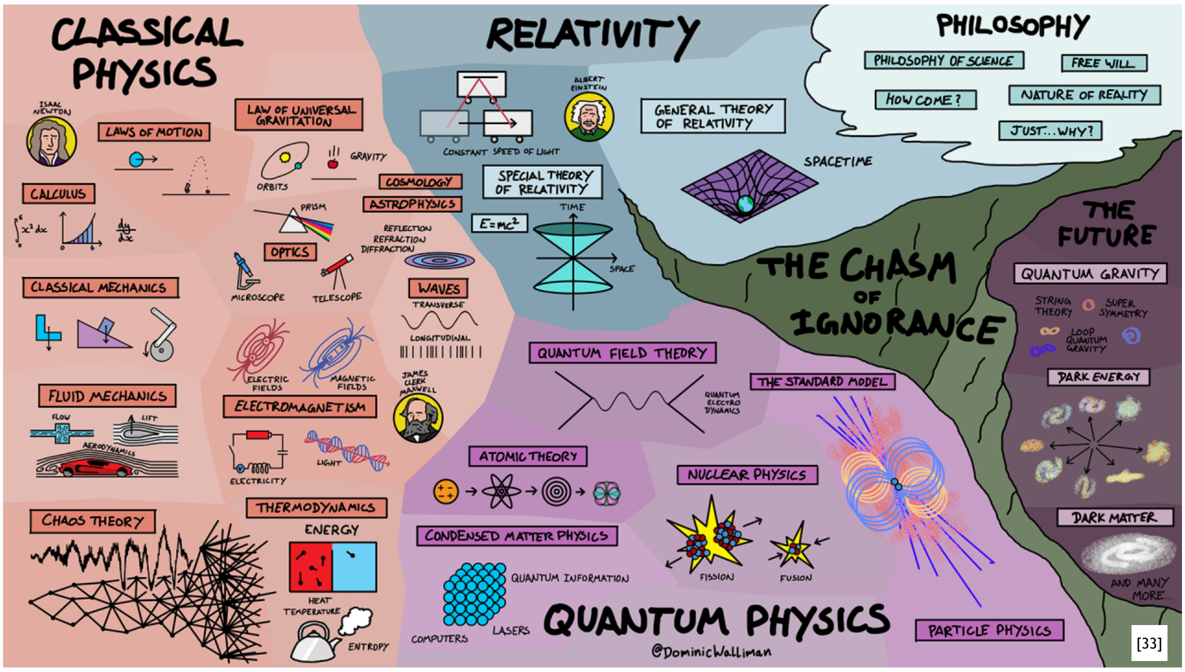


Source: *The Economist*

[32]

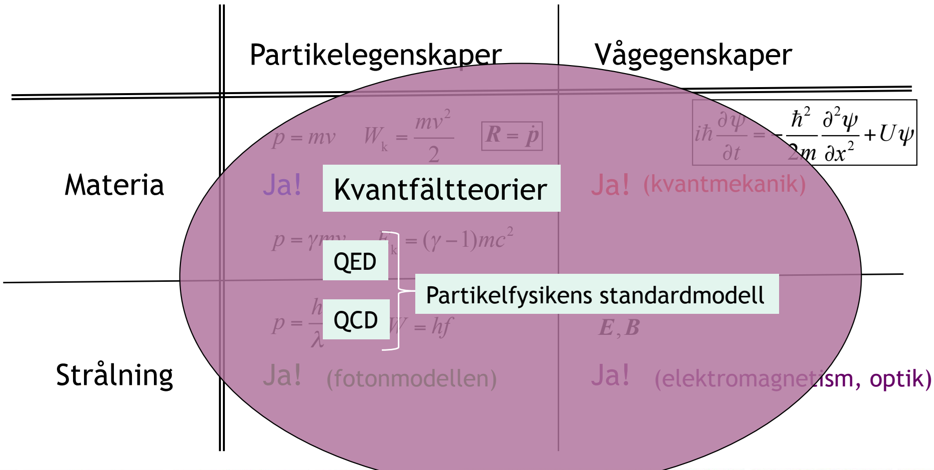
Läget idag

Ett sätt at se på det:



[33]

Läget idag



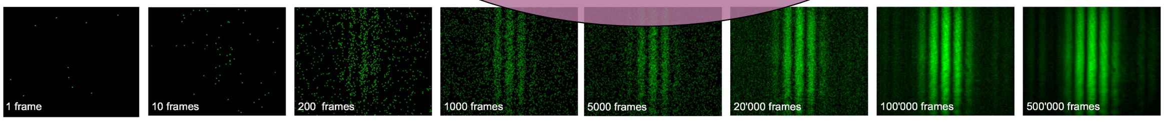
	Partikelegenskaper	Vågegenskaper
Materia	$p = mv \quad W_k = \frac{mv^2}{2} \quad \boxed{\boldsymbol{R} = \dot{\boldsymbol{p}}}$ Ja! $p = \gamma mv \quad W_k = (\gamma - 1)mc^2$	$\boxed{i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\psi}{\partial x^2} + U\psi}$ Ja! (kvantmekanik)
Strålning	$p = \frac{h}{\lambda} \quad W = hf$ Ja! (fotonmodellen)	$\boldsymbol{E}, \boldsymbol{B}$ Ja! (elektromagnetism, optik)

Kvantfältteorier

QED

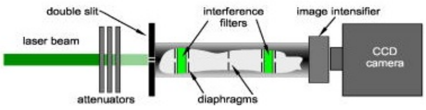
QCD

Partikelfysikens standardmodell



[9]

Dubbelspaltexperiment med fotoner (2005)



http://dominicwalliman.com

Källor

[0] http://researcher.ibm.com/researcher/view_project_subpage.php?id=4252
Fe-atomer på Cu(111).
[0a] http://www.farnamstreetblog.com/2015/01/richard-feynman-knowing-something/
[0b] Richard P. Feynman i *The Character of Physical Law* (Penguin Books, 199[illegible]) [illegible] 129
[1] http://en.wikipedia.org/wiki/File:Richard_Feynman_Nobel.jpg
[1b] http://www.davidrumsey.com/luna/servlet/detail/RUMSEY~[illegible]~1~[illegible]0692~[illegible]50611:Europe–
Från The Times atlas, 1895
[1b2] http://www.massingnickel.se/bussar.html
[1c] T. L. Dimitrova & A. Weis, *American Journal of Physics* **76** (200[illegible]) 137
se också http://photonterrace.net/en/photon/duality/

solvay Se ockås http://www.youtube.com/watch?v=8GZd[illegible]ouzBY

[2] http://en.wikipedia.org/wiki/File:B[illegible]oglie_Big.jpg
[3] http://www.divphysics.c[illegible]/2013/04/0[illegible]/in-memoriam-dr-akira-tonomura-1942-2012/
[4] http://en.wikipedia.[illegible]/wiki/File:Er[illegible]n_Schrödinger.jpg
[5] http://en.wikipedia.org/w[illegible]i/File:Phthalocyanine-3D-balls.png
[6
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[10]

Vidareläsning

Kapitel 4 i *Ett utsökt universum*
av Brian Greene

Quantum - A Guide for The Perplexed
av Jim Al-Khalili

EJ KLART!